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A WARM HOT INTERGALACTIC MEDIUM TOWARDS 3C 120?

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ABSTRACT

We observed the Seyfert I active galaxy/broad line radio galaxy 3C 120 with the *Chandra* high energy transmission gratings and present an analysis of the soft X-ray spectrum. We identify the strongest absorption feature (detected at $> 99.9\%$ confidence) with O VIII Lyα (FWHM = 1010^{+295}_{-265} km s^{-1}), blueshifted by -5500 ± 140 km s^{-1} from systemic velocity. The absorption may be due to missing baryons in warm/hot intergalactic medium (WHIGM) along the line-of-sight to 3C 120 at $z = 0.0147 \pm 0.0005$, or it could be intrinsic to the jet of 3C 120. Assuming metallicites of $\sim 0.1 Z_{\odot}$, we estimate an ionic column density of $N_{O\ viii} > 3.4 \times 10^{16}$cm^{-2} for WHIGM and a filament depth of $< 19 h_{70}^{-1}$ Mpc. We find a baryon overdensity > 56 relative to the critical density of a Λ-dominated cold dark matter universe, which is in reasonable agreement with WHIGM simulations. We detect, at marginal significance, absorption of O VIII Lyα at $z \sim 0$ due to a hot medium in the Local Group. We also detect an unidentified absorption feature at ~ 0.71 keV. Absorption features which might be expected along with O VIII Lyα, were not significant statistically. Relative abundances of metals in the WHIGM and local absorbers may therefore be considerably different from solar.

Subject headings: galaxies: active – galaxies: individual (3C 120) – galaxies: Seyfert – techniques: spectroscopic – X-rays: galaxies – X-rays: galaxies

1. INTRODUCTION

Around half of the baryons in the universe (by mass) should reside in intergalactic filaments of a warm/hot intergalactic medium (WHIGM) (Cen *et al.* 1995, Davé *et al.* 2001). These filaments are believed to be shock-heated to 10^5 K $<$ T $< 10^7$ K (see e.g. Cen & Ostriker, 1999). Most WHIGM may lie at the hotter end of this temperature range (Cen *et al.* 2001), so high spectral resolution X-ray detectors such as those aboard *Chandra* and *XMM-Newton* are best placed for investigating the 'hot' component of the missing baryons. 'Hot' WHIGM may recently have been discovered for the first time at X-ray energies (Nicastro *et al.* 2002; Fang *et al.* 2002a,b; Rasmussen *et al.* 2002; McKernan *et al.* 2003).

We observed the X-ray source 3C 120 with the High Energy Transmission Grating Spectrometer (or HETG–Markert, *et al.* 1995) and ACIS aboard *Chandra* . 3C 120 (z=0.033, Michel & Huchra 1988) is classified both as a Seyfert 1 active galactic nucleus (AGN) and a broad line radio galaxy (BLRG). Here we discuss the serendipitous discovery of an O VIII Lyα absorption signature in the 3C 120 spectrum, likely due to WHIGM along the line of sight.

2. OBSERVATIONS AND DATA

We observed 3C 120 with the *HETGS* on board *Chandra* on 2001 December 21 for ~ 58 ks, beginning at UT 11:13:52. The *HETGS* consists of two grating assemblies, a High-Energy Grating (HEG) and a Medium-Energy Grating (MEG). Only the summed, ± 1 order *Chandra* grating spectra were used in our analysis. We found the counts distribution as a function of cross-dispersion angle could be approximated by a Gaussian model with widths in the range $\sim 0.46 - 0.49''$ for the ± 1 orders of the MEG. This Gaussian model is consistent with a point source, although there is emission of $\sim 6\%$ peak emission at $\sim +3''$, possibly due to the extended jet. We accumulated grating spectra along the dispersion direction and within $\sim \pm 3.6''$ of the peak in the cross-dispersion direction. The mean MEG and HEG total count rates were 0.8134 ± 0.0038 and 0.3770 ± 0.0031 cts/s respectively. We extracted spectra and spectral responses exactly as described in Yaqoob *et al.* (2003) and obtained a net exposure time of 57,224 s (including a deadtime factor of 0.01618). During the observation 3C 120 did not vary much; the light-curve yielded an excess variance of 0.0043 ± 0.0007 (Turner *et al.* 1999). Since the HEG bandpass only extends down to ~ 0.8 keV we use the MEG as the primary instrument. We used *C*-statistic for finding best-fit model parameters, and quote 90% confidence, one-parameter statistical errors. The harder spectrum, including the Fe-K emission line will be discussed elsewhere.

The ACIS CCDs have been undergoing a low-energy QE degradation, due to absorption by contaminants [5]. There is a model of the contamination pertinent for pure ACIS data (without the gratings). We can use this model as a 'worst case' to estimate the effects on the continuum. Thus, we will give results with and without corrections using the ACIS QE degradation model in XSPEC v11.2 (`acisabs`), using default absorption by the contaminants C, H, O, and N in the ratio 10:20:2:1 by number of atoms.

All spectral fits were done in the 0.5–5 keV energy band, excluding the 2.0–2.5 keV region, which suffers from systematics due to limitations in the calibration of the X-ray telescope [6]. First we fitted spectra binned coarsely at 0.32A, in order to compare with previous CCD spectra. A simple model consisting only of a single power–law ($\Gamma = 1.69 \pm 0.02$) and Galactic absorption of 1.23×10^{21} cm^{-2} (Elvis, Lockman & Wilkes 1989) fit the data adequately, with residuals < 30 % over the fitted energy band. The inverted photon spectrum and residuals are shown in Fig. 1. The residuals at ~ 0.8 keV

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[5] http://cxc.harvard.edu/cal/Links/Acis/acis/Cal_prods/qeDeg/index.html
[6] http://asc.harvard.edu/udocs/docs/POG/MPOG/node13.html

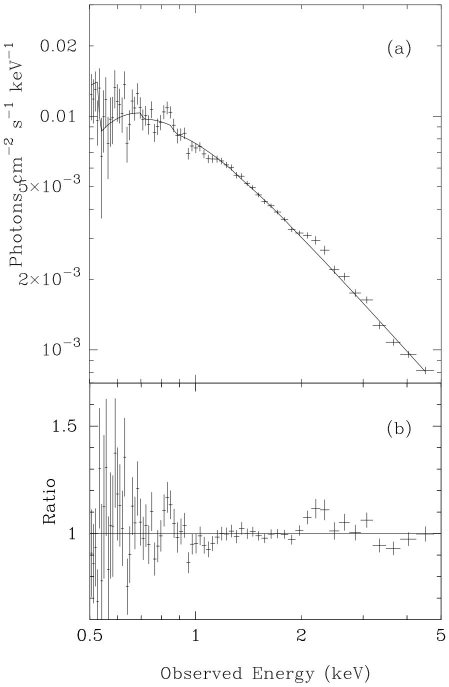

FIG. 1.— Inverted photon spectrum (a), and data/model ratios (b), when 3C 120 MEG data are fitted with a simple power-law plus Galactic absorption model over the 0.5–5 keV band. The 2.–2.5 keV region was omitted during the fit because large changes in the effective area as function of energy due to the telescope response, are not pefectly modeled in the response function. The ~ 0.8 keV region also coincides with sharp changes in the effective area for this observation, but the magnitude of the systematic errors is smaller so these data were retained in the fit.

coincide with sharp changes in effective area and are likely due to the limitations of the calibration. Including the ACIS degradation model requires a soft excess in the data, which we modeled as a broken power–law. We found a best-fit soft X-ray index of 2.58 ± 0.02, a hard X-ray index of 1.76 ± 0.02 and a break energy of $1.06^{+0.04}_{-0.06}$ keV.

We compared our data with previous CCD observations by modeling the MEG data with two absorption edges and a single power law (and Galactic absorption). We find threshold optical depths of $\tau < 0.06$ and $\tau = 0.06^{+0.05}_{-0.05}$ at 90% confidence for O VII and O VIII respectively. These small optical depths do not alter the power-law index. These optical depths agree reasonably well with $\tau < 0.01$ (O VII) and $\tau < 0.05$ (O VIII) found by *ASCA* (Reynolds, 1997). Including ACIS degradation yielded $\tau < 0.11$ and $\tau < 0.07$ for O VII and O VIII respectively. Finer spectral binning (0.02A) does not change these results.

3. DISCRETE SPECTRAL FEATURES

The MEG spectrum of 3C 120 is shown in detail in Fig. 2(a) (0.6–0.8 keV) and Fig. 2(b) (0.8–1.4 keV). Strong absorption appears at ~ 0.645 keV and ~ 0.71 keV in the observed frame in Fig. 2(a). We identify the feature at ~ 0.645 keV with O VIII Lyα (0.653 keV rest–frame) blueshifted by ~ -5500 km s^{-1} from 3C 120 systemic velocity. The feature at ~ 0.71 keV remains unidentified since all absorption transitions considered for this feature should yield strong absorption features elsewhere in the spectrum. For all spectral fitting hereafter we use a binsize of 0.02A ($\approx$ MEG FWHM resolution). Since there are bins with zero counts in the O VIII Lyα feature, the data are of limited statistical quality, modeling the absorption profile with a Voigt function is not warranted. Therefore we modeled the profile with a simple window function, whereby over an energy interval W, centered on some energy, E, a fraction f, of the continuum is absorbed.

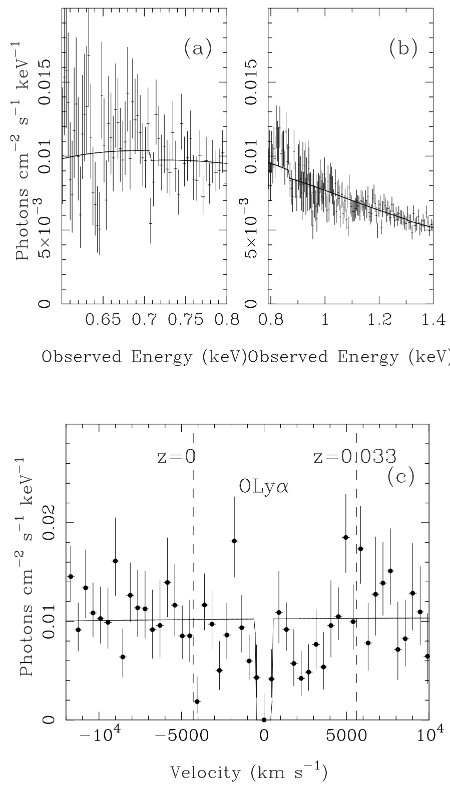

FIG. 2.— (a) 3C 120 MEG observed photon spectrum between 0.6–0.8 keV compared to the best-fitting single power–law model (modified by Galactic absorption). The data are binned at 0.08A. The most significant candidate absorption features in the spectrum lie around ~ 0.65 keV and ~ 0.71 keV. (b) As for (a) but between 0.8–1.4 keV and the data are binned at 0.04A between 0.9–1.4 keV. (c) Velocity profile from combined ± 1 order *Chandra* MEG data centered on the O VIII Lyα feature at 0.6443 keV. A negative velocity indicates a blueshift relative to this energy. Also indicated are the local ($z = 0$) and systemic ($z = 0.033$) rest-frames. Superimposed is the best–fit absorption line model and continuum (black line). There appear to be two components of O VIII Lyα absorption, one marginally significant due to hot medium in the Local Group of galaxies at $z \sim 0$ and the other significant, at ~ -5500 km s^{-1} blueshifted from 3C 120 (see Table 1). There is no absorption at systemic velocity. Parameters from the model fits are given in Table 1 and can be compared with the FWHM MEG velocity resolution of 360 km s^{-1} for O VIII Lyα , in the observed energy frame.

Table 1 shows the results of spectral fitting the O VIII Lyα profile. Also in Table 1 are the corresponding results when ACIS degradation is included, and the best–fit to the unidentified feature at ~ 0.71 keV (also fit with a window function plus ACIS degradation). The O VIII Lyα profile parameters are not strongly influenced by ACIS degradation and the C–statistic improves by > 18 upon the addition of the absorption-line model (which corresponds to $> 3\sigma$ significance for three additional parameters). The O VIII Lyα feature has FWHM= 1010^{+295}_{-265} km s^{-1}, EW= $2.17^{+0.57}_{-0.63}$ eV and is strongly blueshifted ($\Delta v = -5500 \pm 140$ km s^{-1}) from 3C 120 systemic velocity. The absorption occurs at $z = 0.0147 \pm 0.0005$ if it is due to intervening WHIGM. O VIII Lyβ absorption is not statistically significant (EW= $0.70^{+1.19}_{-0.70}$ eV) when the data are fit with a Gaussian model with the same FWHM and z as O VIII Lyα in Table 1. We tested the data for O VII (r) , Ne IX (r) and Ne X Lyα absorption in the same way and found EW<4.12

eV and <1.78 eV for O VII (r) and Ne X Lyα respectively. There is weak evidence of Ne IX (r) *emission* so we could not find a meaningful upper limit on the absorption EW for this feature.

An independent confirmation of the significance of the O VIII Lyα feature was obtained as follows. From the best-fitting continuum, the instrument effective area, and the exposure time, we estimated if there were *no* absorption feature we should expect a mean of 13.8 photons in the fitted energy interval containing the feature (Table 1). We observed 2 photons in this energy interval (13 bins out of 126 over the range $z = 0$ to $z = 0.033$). The Poisson probability of obtaining this result is $\sim 0.00975 \times (126/13)\%$ so the confidence level of the detection of the feature is $> 99.9\%$ (i.e. $> 3\sigma$). We verified this result by performing 10^7 simulations of the continuum, with *no* absorption feature. We note that a 9% decrease in the level of the continuum is allowed before the detection significance of the absorption feature drops below 3σ. Both the O VIII Lyα and 0.71 keV absorption features are detected separately in the -1 and +1 arms of the MEG. Absorption models improved the C–statistic by $17.3, 16.0$ for O VIII Lyα and by $24.8, 17.4$ for the $\sim$ 0.71keV feature in the $-1, +1$ arms respectively. Thus it is extremely unlikely that either feature is due to a statistical fluctuation since the probabilities above do not take into account detections in *both* arms of the MEG.

Fig. 2 (c) shows a velocity spectrum centered on the O VIII Lyα feature. Negative velocity indicates blueshift relative to the observed energy of the O VIII Lyα feature. Superimposed is the best-fitting continuum model and absorption line profile as described below (see also Table 1). The dashed lines correspond to rest–frame velocities at $z = 0$ and $z = 0.033$ respectively. The O VIII Lyα is blueshifted by ~ -5500 km s^{-1} from 3C 120 systemic velocity ($z = 0.033$) and there may be absorption at ~ -4500 km s^{-1} in Fig. 2 (c), close to $z = 0$, presumably due to a hot medium in the Local Group, as observed elsewhere (eg Nicastro *et al.* 2002, Fang *et al.* 2002b, Rasmussen *et al.* 2002, McKernan *et al.* 2003). However, the relativistic jet in 3C 120 could also account for the large outflow velocity (see §4). There is no absorption near the 3C 120 systemic velocity ($z = 0.033$).

TABLE 1. ABSORPTION FEATURES IN THE MEG SPECTRUM OF 3C 120

	O VIII Lyα with ‘`acisabs`’	O VIII Lyα no correction	$\sim$ 0.71 keV feature with ‘`acisabs`’
ΔC [a]	–18.5	–18.4	–17.8
E (eV)	644.3 ± 0.3	644.3 ± 0.3	708.5 ± 0.4
Δ v (km s^{-1}) [b]	-5500 ± 140	-5500 ± 140	…
z_{eff}	0.0147 ± 0.0005	0.0147 ± 0.0005	…
Width (eV)	$2.17^{+0.57}_{-0.63}$	$2.20^{+0.52}_{-0.70}$	$2.00^{+1.40}_{-0.76}$
FWHM (km s^{-1})	1010^{+295}_{-265}	1025^{+245}_{-325}	930^{+655}_{-355}
EW (eV)	$2.17^{+0.57}_{-0.78}$	$2.20^{+0.52}_{-0.92}$	$2.00^{+1.40}_{-0.54}$
f[c]	$1.00^{+\cdots}_{-0.19}$	$1.00^{+\cdots}_{-0.19}$	$1.00^{+\cdots}_{-0.38}$
Γ_1	$2.58^{+0.10}_{-0.08}$	…	$2.56^{+0.09}_{-0.07}$
Γ_2	1.76 ± 0.02	1.69 ± 0.02	1.76 ± 0.02
E_b (keV)	$1.06^{+0.04}_{-0.06}$	…	$1.06^{+0.04}_{-0.05}$

NOTE. — Absorption-line parameters measured from the MEG spectrum, with (O VIII Lyα and $\sim$ 0.71 keV feature) and without (O VIII Lyα only) the ACIS degradation model. The model continuum with ACIS degradation was a broken power–law and the model without degradation was a single power–law. A window function was used to model the O VIII Lyα and $\sim$ 0.7 keV absorption features, whereby a fraction f of the continuum is absorbed over an energy interval, W, centered on an energy, E (see text for details). All measured quantities refer to the observed frame, already corrected for the instrument response. Errors are 90% confidence for one interesting parameter ($\Delta C = 2.706$). Velocities have been rounded to the nearest 5 km s^{-1}. [a] Improvement in C-statistic when the indicated absorption feature is added to the continuum-only model (which includes Galactic absorption). All values of ΔC here correspond to $> 3\sigma$ significance for the addition three free parameters. [b] Blueshift of feature center energy relative to O VIII Lyα in 3C 120 frame. The rest-frame energy of O VIII Lyα is 0.6536 keV. [c] Covering fraction for the absorption-line model. For a value of $f = 1$ the width of the feature is equal, by definition, to the equivalent width.

4. DISCUSSION

We identify the most prominent absorption feature in the soft X-ray spectrum of 3C 120 with blueshifted O VIII Lyα (~ -5500 km s^{-1} relative to systemic, see Table 1). There may also be absorption at $z = 0$ due to O VIII Lyα in the Local Group of galaxies and there is unidentified absorption at $\sim$ 0.71 keV. The O VIII Lyα outflow velocity is considerably larger than in ‘warm absorbers’ in Seyfert 1 AGN (typically a few hundred km s^{-1}). O VIII Lyα absorption possibly due to intervening, non-local WHIGM has been observed in the spectrum of the BL Lac PKS-2155-304 by Fang *et al.* (2002a) who report a similar width (< 1450 km s^{-1}) to our feature (1010^{+295}_{-265} km s^{-1}), but weaker (EW= $0.48^{+0.25}_{-0.19}$ eV versus EW= $2.17^{+0.57}_{-0.78}$ eV). Absorption by a hot medium in the Local Group ($z \sim 0$) has also been detected towards PKS-2155-304 (Fang *et al.* 2002a, Nicastro *et al.* 2002), 3C 273 (Rasmussen *et al.* 2002, Fang *et al.* 2002b) and NGC 4593 (McKernan *et al.* 2003), but these features are generally weaker than the O VIII Lyα feature in 3C 120 .

From Table 1, O VIII Lyα FWHM$<$ 1305 km s^{-1}, so the path length of a putative WHIGM filament has an upper limit $\sim 19h_{70}^{-1}$ Mpc, otherwise differential Hubble flow would broaden the line. Also, using EW$>$ 1.39eV and a curve–of–growth analysis, we obtain a column density of $N_{O\ viii} > 3.4 \times 10^{16}$cm^{-2} (at 90% confidence). The EW upper limits on O VII (r), O VIII Lyβ and Ne X Lyα discussed in §3 above, are consistent with this curve–of–growth analysis. Assuming all O is in O VIII , and an O abundance of ~ 0.1 solar (or $\sim 8.5 \times 10^{-5}$A$_{\rm H}$), the corresponding neutral Hydrogen column is $\geq 4.0 \times 10^{20}$cm^{-2}. For a filament depth $< 19h_{70}^{-1}$ Mpc, we obtain an electron density $n_e > 6.7 \times 10^{-6}$cm^{-3}. If we assume the mean baryon density in the universe (Ω_b) relative to the critical density ($\Omega_{\rm crit} = 9.2 \times 10^{-30} h_{70}^2$ g cm^{-3}) is $\Omega_b h_{70}^2 = 0.0224 \pm 0.0009$ (Spergel *et al.* 2003), then using $m_{\rm H} = 1.7 \times 10^{-24}$ g, the mean number density of baryons ($\bar{N}_b$) in the universe is $\bar{N}_b = 1.2 \times 10^{-7}$cm^{-3}. Equating n_e with $\bar{N}_b$, we find a baryon overdensity ($O_b > 56\Omega_b h_{70}^2$) in the WHIGM. From WHIGM simulations for a variety of Λ-dominated cold dark matter universes, O_b in WHIGM is expected to peak in the range $\sim 10-30$, for distributions where $70-80\%$ of WHIGM baryons lie in the range $O_b \sim 5-200$ (Davé *et al.* 2001). Our results indicate that WHIGM may indeed lie in diffuse, hot, intergalactic filaments, slightly denser than predicted by simulations. The high ionization state of the WHIGM filament is consistent with previous observations of 3C 120 in the UV with *IUE* , which exhibit no obvious Lyα absorption (Kinney *et al.* 1991). There is also no evidence for absorption in the optical band (Baldwin *et al.* 1980) in 3C 120. The absence of strong absorption features from Ne IX (r) and Ne X Lyα may indicate that metal abundances in WHIGM are considerably different from solar abundances.

Is it possible that the absorption feature in 3C 120 is actually due to intrinsic absorption in the jet? The O VIII Lyα feature could originate in an outflow of $\sim$ 5500 km s^{-1} rel-

ative to systemic velocity and many QSOs can exhibit such high velocity outflows. Optically bright QSOs exhibit C IV absorption signatures at 5,000–65,000 km s^{-1} (Richards *et al.* 1991). Very broad ($\sim 30,000$ km s^{-1}) absorption features have been observed in BL-Lacs with *ROSAT* (Madejski *et al.* 1991), however these are much broader than the features in 3C 120. *XMM-Newton* observations have found high-velocity outflows in PG1211+143 ($\sim 0.08c$) and PG0844+349 ($\sim 0.2c$) (Pounds *et al.* 2003a,2003b). If absorption signatures in 3C 120 arise in the jet, they might extend nearly to systemic velocity due to jet acceleration or deceleration. A hint of absorption around ~ 2500 km s^{-1} in Fig. 2 (c), suggests we cannot rule this out. Interestingly, all the other X-ray sources where WHIGM detection has been claimed (Fang *et al.* 2002a,b; Nicastro *et al.* 2002; Rasmussen *et al.* 2002) possess a jet closely aligned to the line-of-sight. However X-ray sources with jets exhibiting WHIGM absorption may simply represent a selection effect. These are more luminous, distant X-ray sources, so are more likely to have detectable WHIGM filaments along their line-of-sight.

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